Advances in modeling of physical processes in plasma-based sources of EUV radiation

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Outline

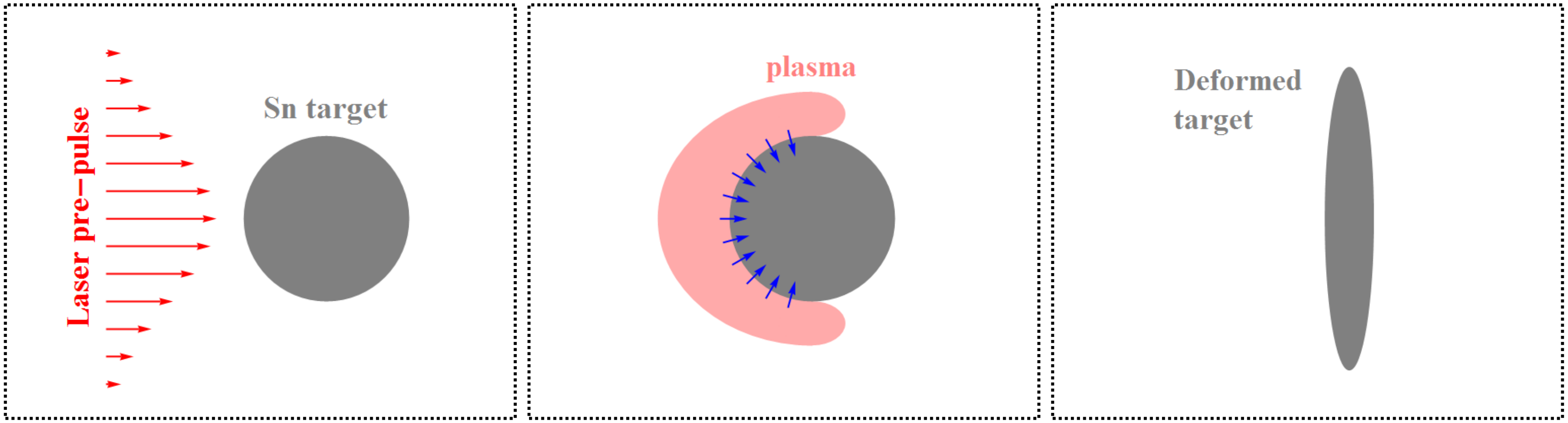
○ Pre-pulse - Modeling of Sn droplet deformation by laser pre-pulse (10 – 50 ns laser pulse, 1-4 us deformation time)

○ Main pulse - Modeling of EUV in-band emission by Sn plasma in LPP (fast multi-charged ions, wide EUV, laser pulse ~ 30 -300ns, characteristic size 100-300 um)

○ Source chamber - Modeling of transfer of Sn fast ions and radiation in gaseous atmosphere of EUV source chamber (1 us; 1 m); Modeling of plasma (gas) expansion between pulses (multi-pulse regime)

"Pre-pulse"
Target deformation: hd modeling approach

1. Laser-target interaction | **2. Plasma-target interaction** | **3. Target deformation**



RZLINE code → modeling of laser-target interaction, plasma formation

Calculation of plasma pressure at the target surface and momentum transfer

OpenFOAM code → hydrodynamics modeling of liquid target deformation

RZLINE code

RZLINE – 2D hydrodynamics code with non-equilibrium ionization state

✓ Euler two-temperature plasma hydrodynamics

✓ Multi-group EUV/UV radiation transport described in diffusion and long characteristic approximations

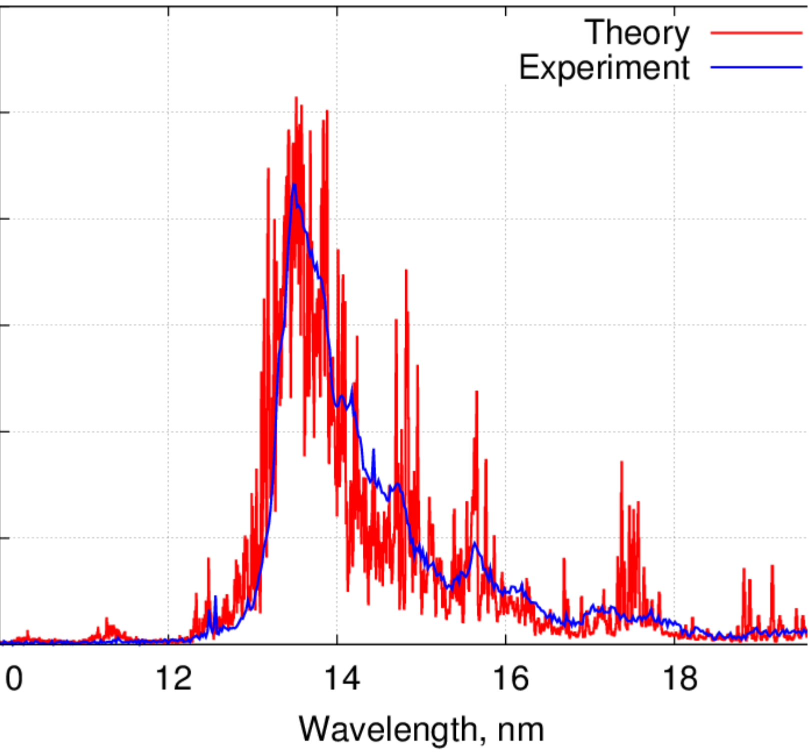
✓ Target evaporation

✓ Laser radiation absorption

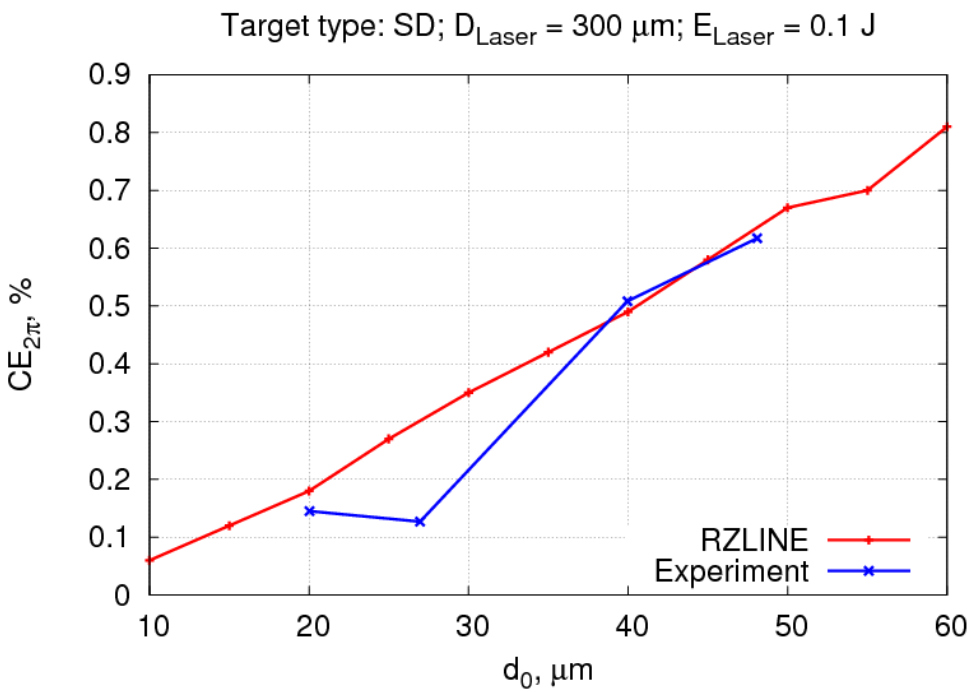
✓ Laser breakdown

RZLINE code validation

EUV emission spectrum from LPP with bulk Sn target
(experiment – ISAN, Moscow, Russia)

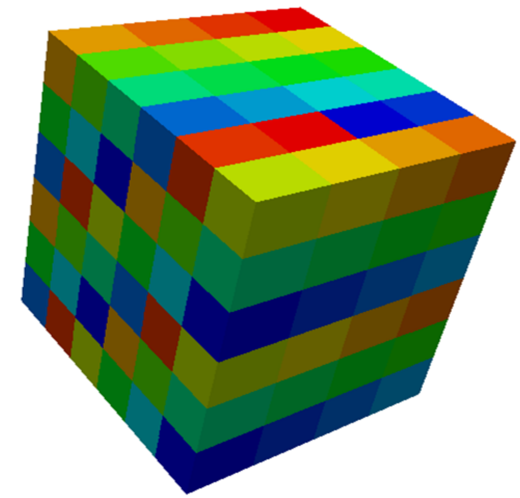


In-band CE for LPP with Sn droplets
(experiments – Gigaphoton –Japan)



3D Hydrodynamics description

Partition of the mesh between processors



+ Volume of Fluid method
+ Two phases (Liquid and Gas)
+ Immiscible fluids
+ Isothermal
+ Viscosity
+ Compressibility

Regular hydrodynamics

+ Surface tension
+ Crushing/merge of droplet(s)
+ Ideal gas equation of state for surrounding gas and constant speed of sound for liquid droplet
+ Surrounding plasma influence through ablation pressure from RZLINE code

Specific

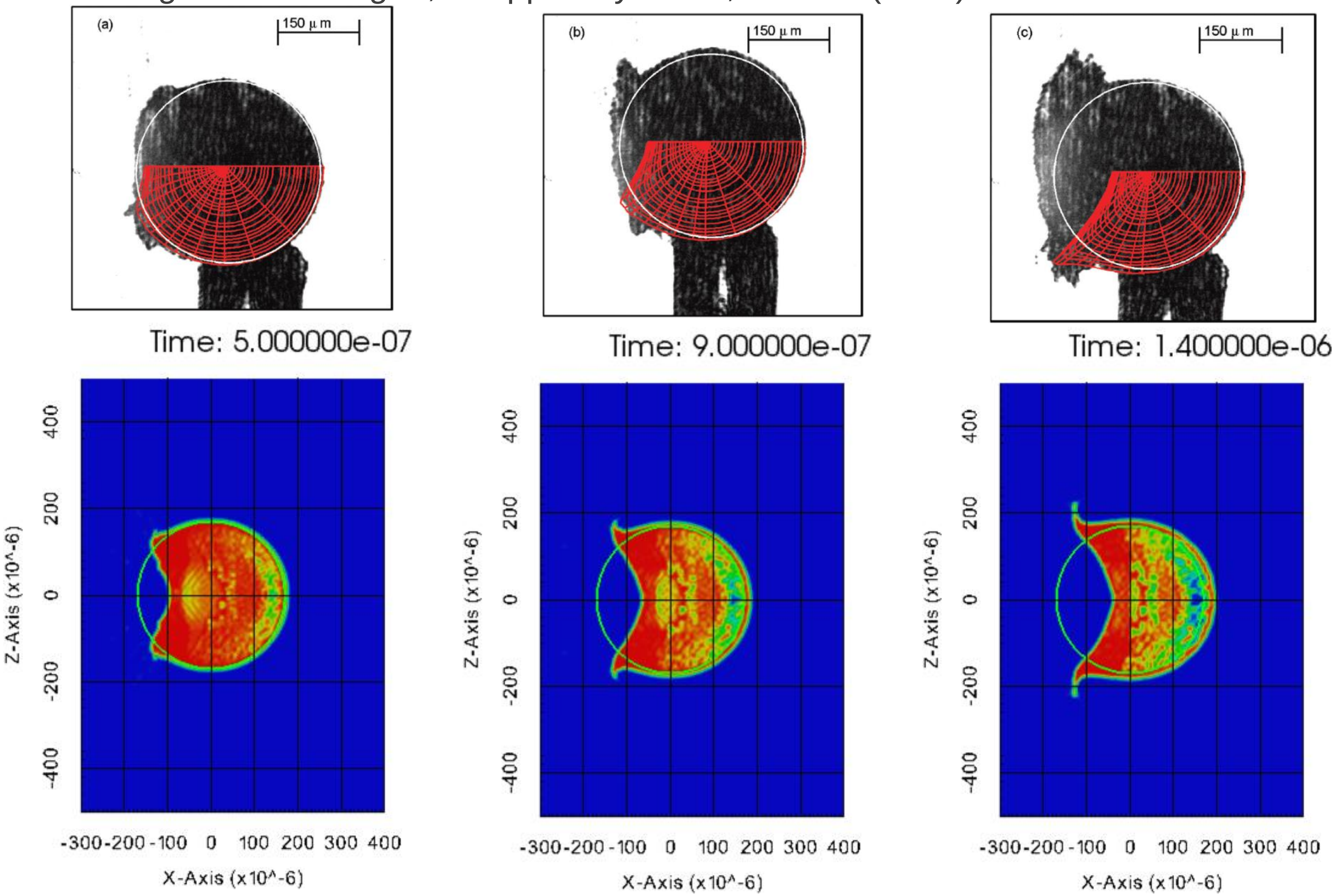
OpenFOAM®

http://www.openfoam.com/

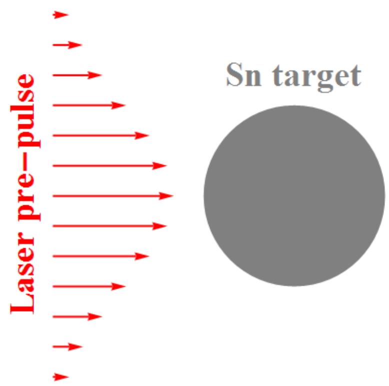
OpenFOAM – free to use 3D simulation software library with extensive CFD and multi-physics capabilities

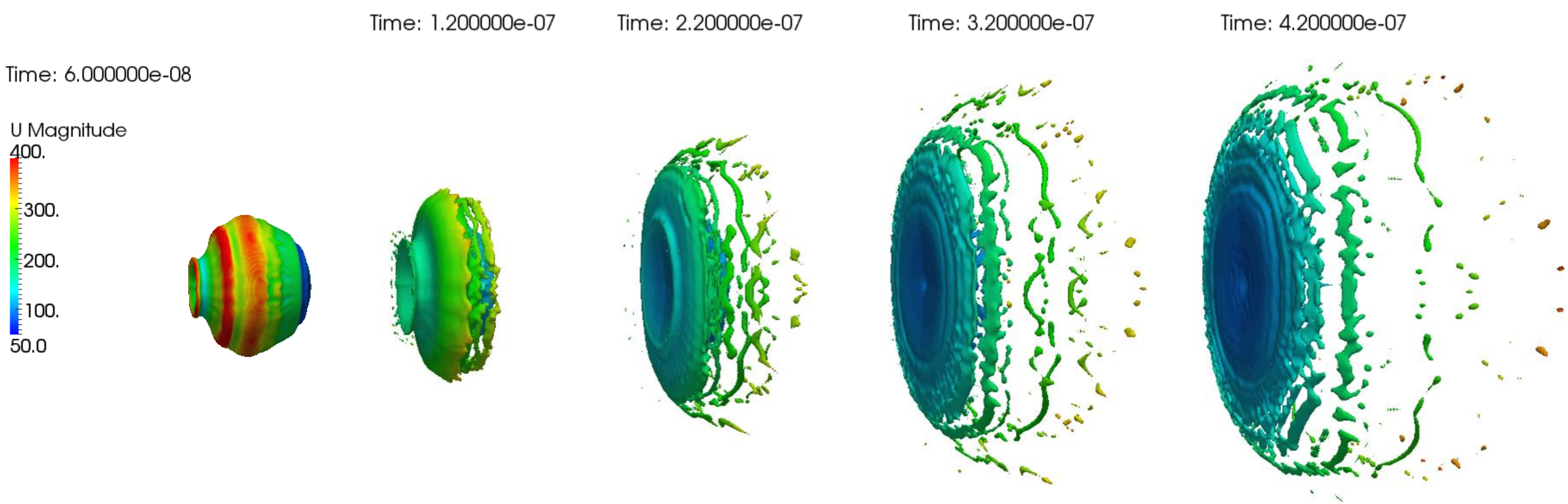
Model validation, details are in appropriate poster

Cavity formation in a liquid Sn droplet driven by laser ablation pressure for an extreme ultraviolet light source target , J. Appl. Phys. 109, 076102 (2011)

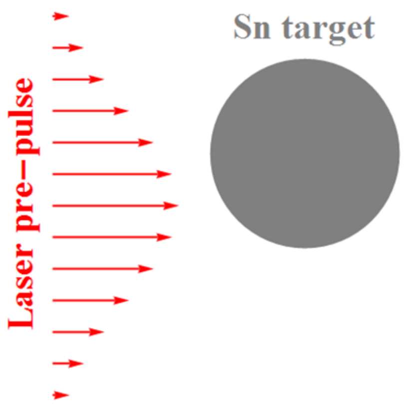


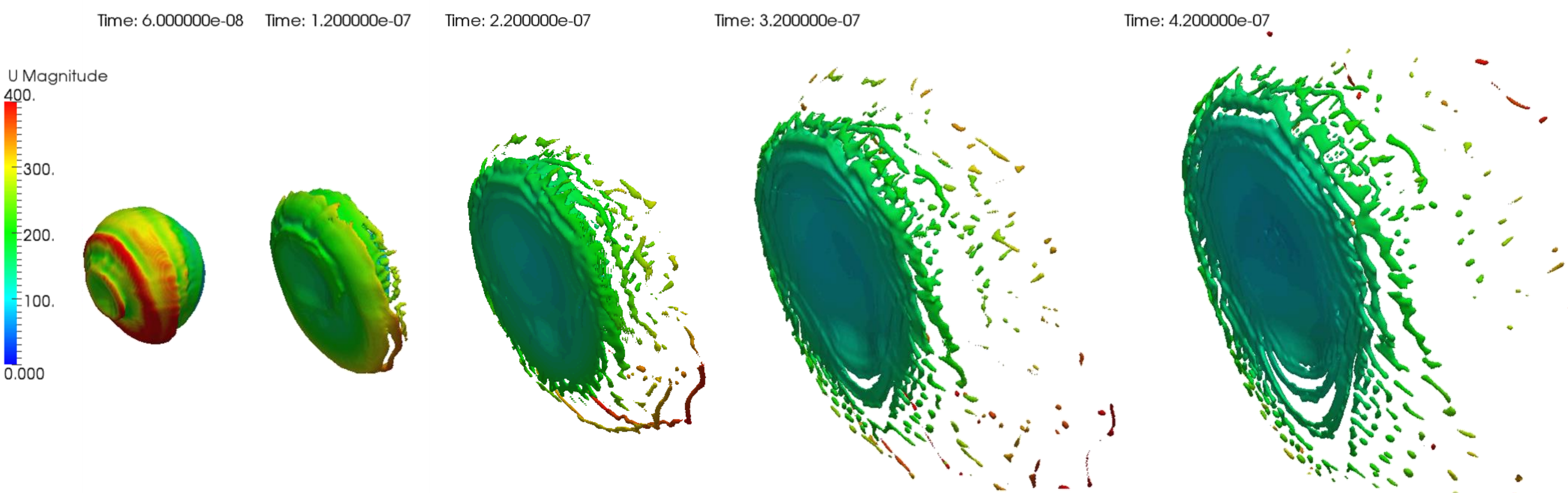
Droplet on the laser axis, details are in appropriate poster s44



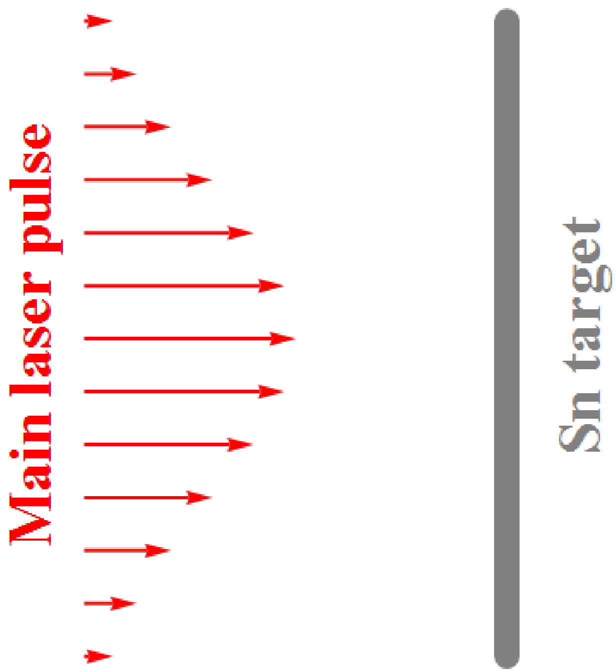


Droplet off laser axis, details are in appropriate poster





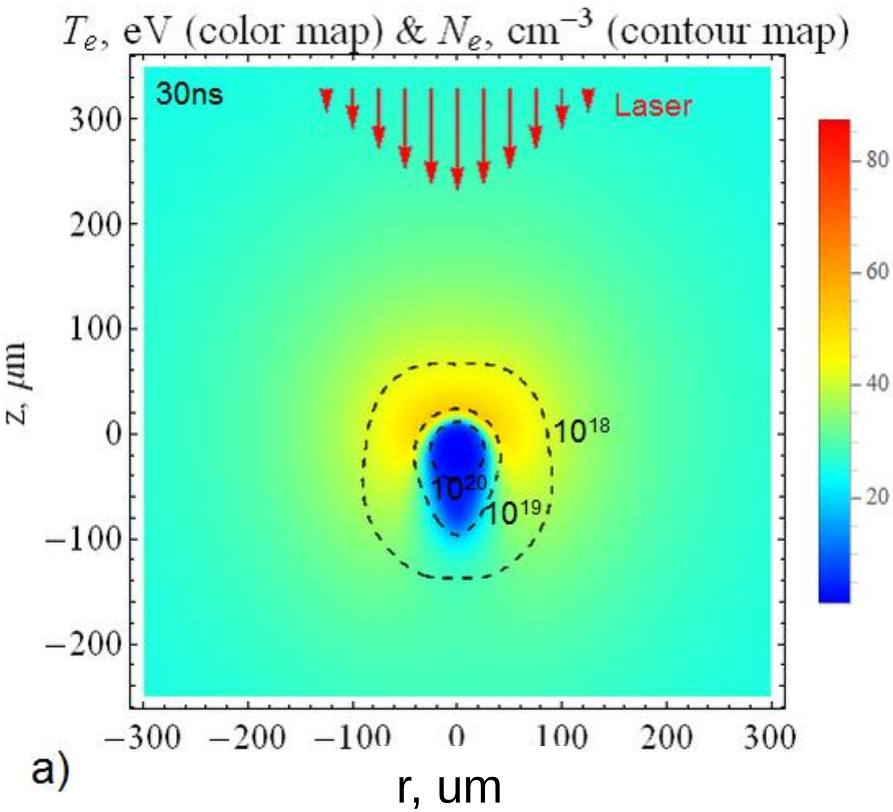
“Main pulse”



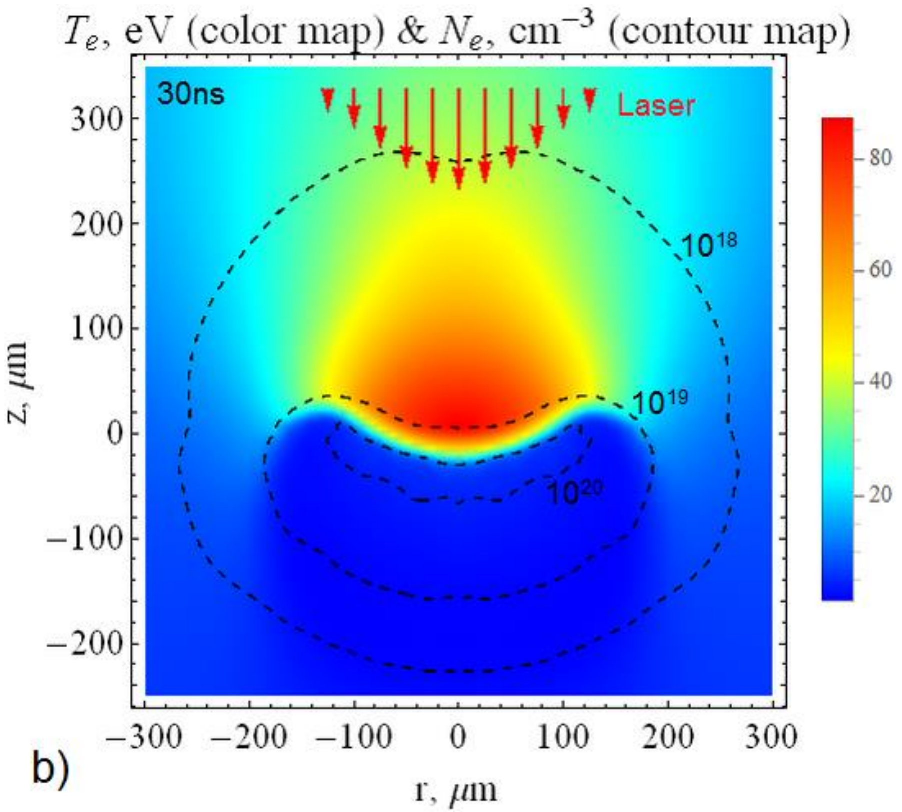
List of some RZLINE outputs

- Spectral characteristics of source
    - ✓ EUV/DUV emission spectra
    - ✓ In-band EUV power with true position of appropriate lines
- Optical characteristics of source
    - ✓ Source size
    - ✓ Emission anisotropy
    - ✓ Detailed optical data for creating images in mirrors
- Debris flows from source
    - ✓ Ions (energy, charge and angle resolved)
    - ✓ Neutrals
    - ✓ Micro/nano-fragments
- Data for video clips
- Graphics data in *.xls form

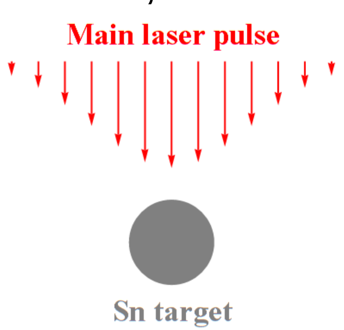
From variant considered in poster s45 droplets versus disk type targets



a)

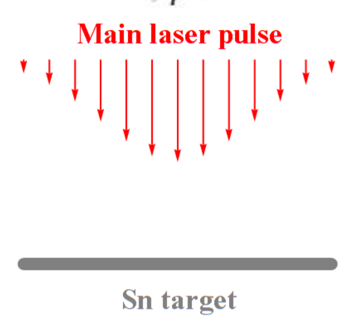


b)



30 um

Laser:
- 300 um Gaussian focal spot
- 510^9 W/cm^2 power density
- 100 ns pulse length

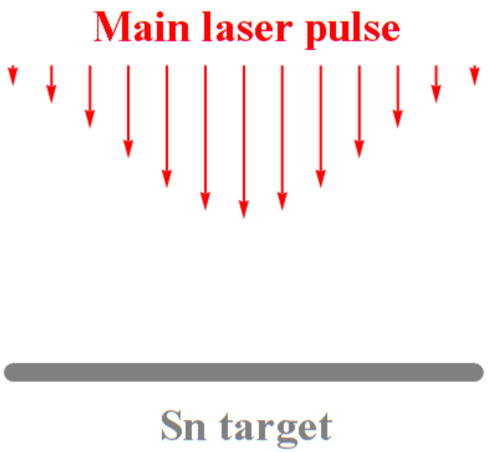


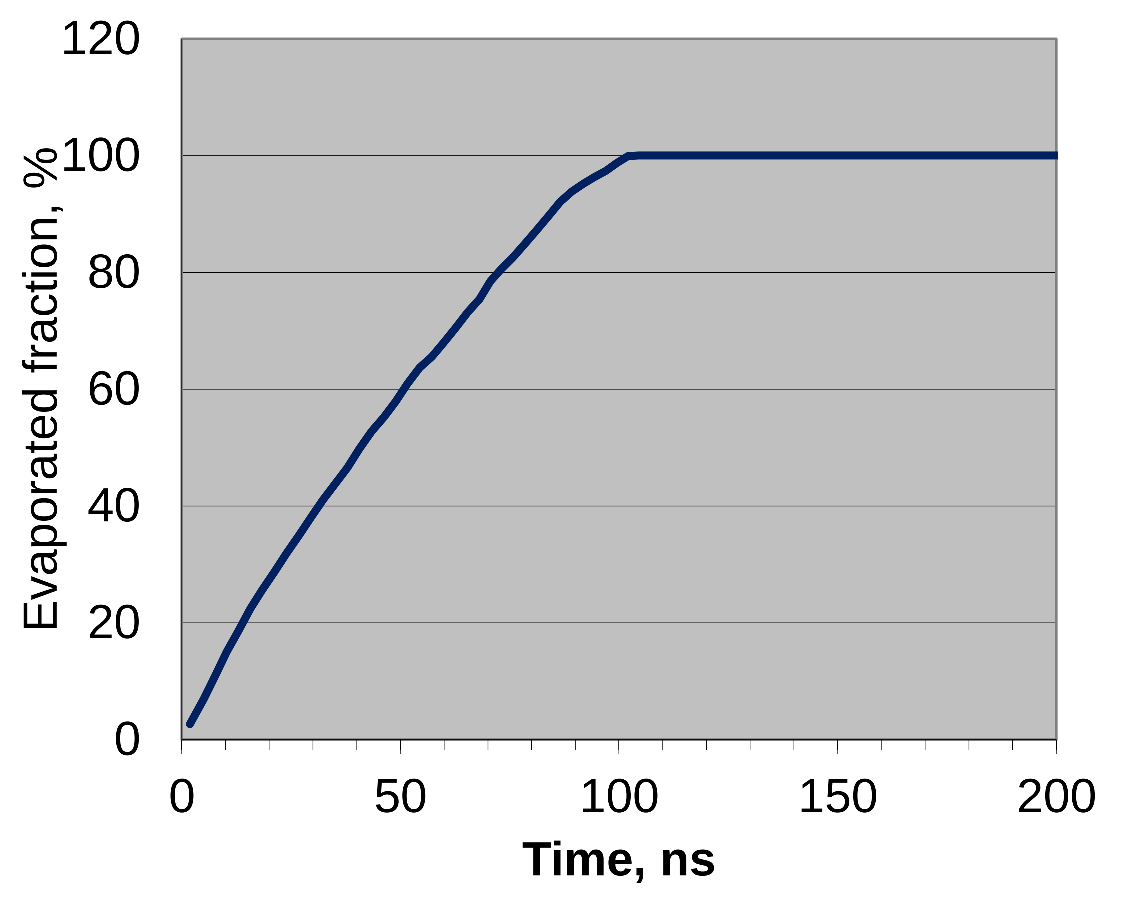
250 um

Some output from RZLINE, relevant to processes in source chamber

Disk type target

300 um Sn disk as a result of pre-pulse at 50 um droplet



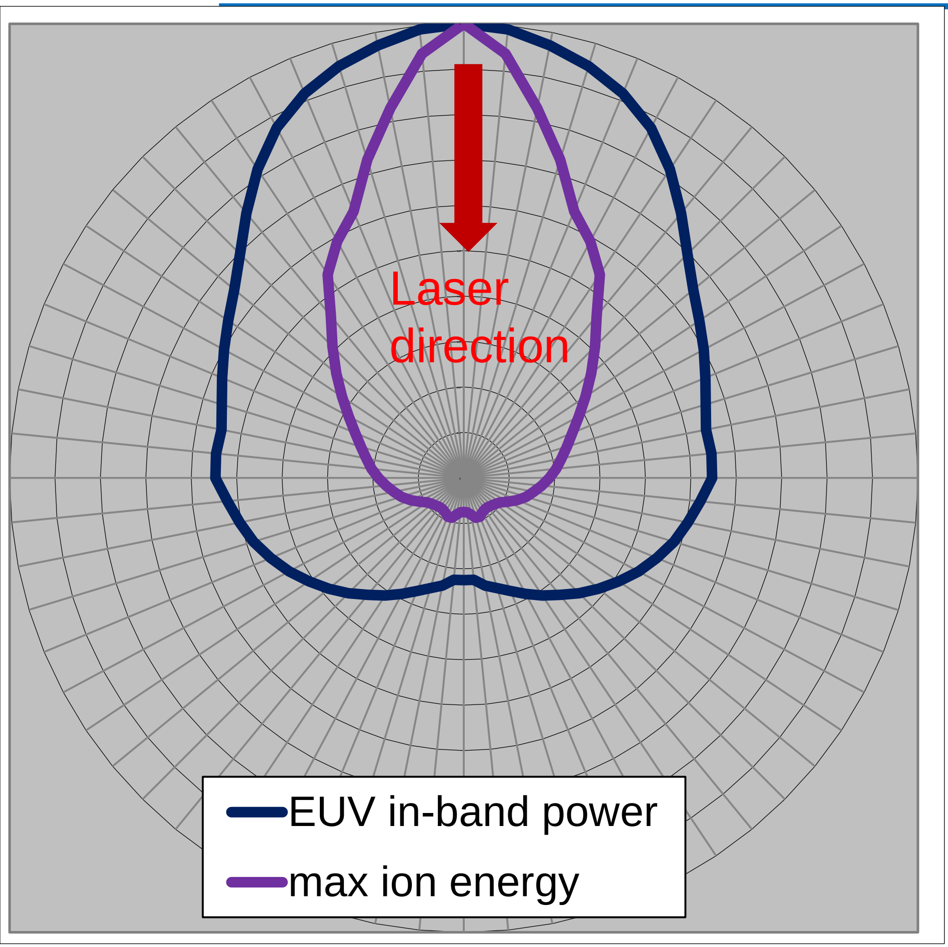


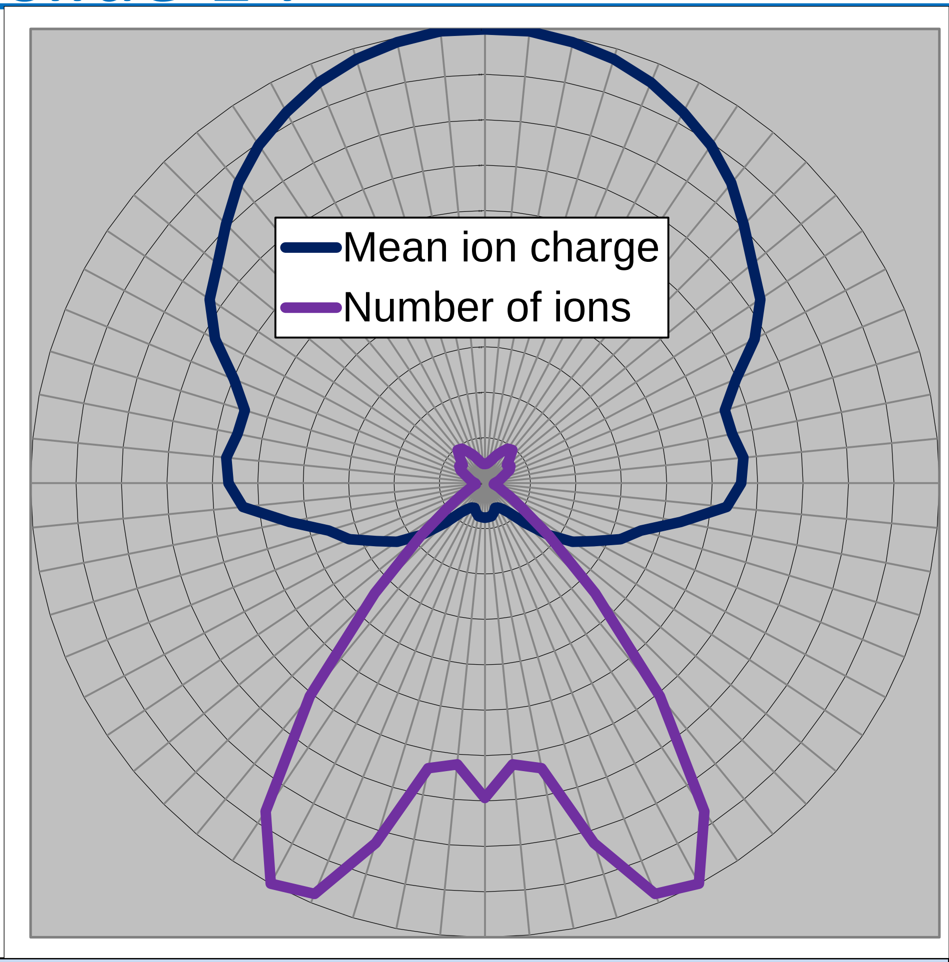
Main laser:

- CO_2 laser 0.6 J
- 350 um Gaussian focal spot
- const power 170 ns pulse

1. Full evaporation of disk during first 100 ns of laser pulse
2. Full evaporation occurs at the axis a little bit earlier (~77 ns)
3. CE here reach 3.4 % in-band in 2pi of condenser mirror, EUV size ~ 300 um
4. Reflection of CO_2 laser – 33%
5. Wide EUV – 32% , Fast ions and plasma – 32%

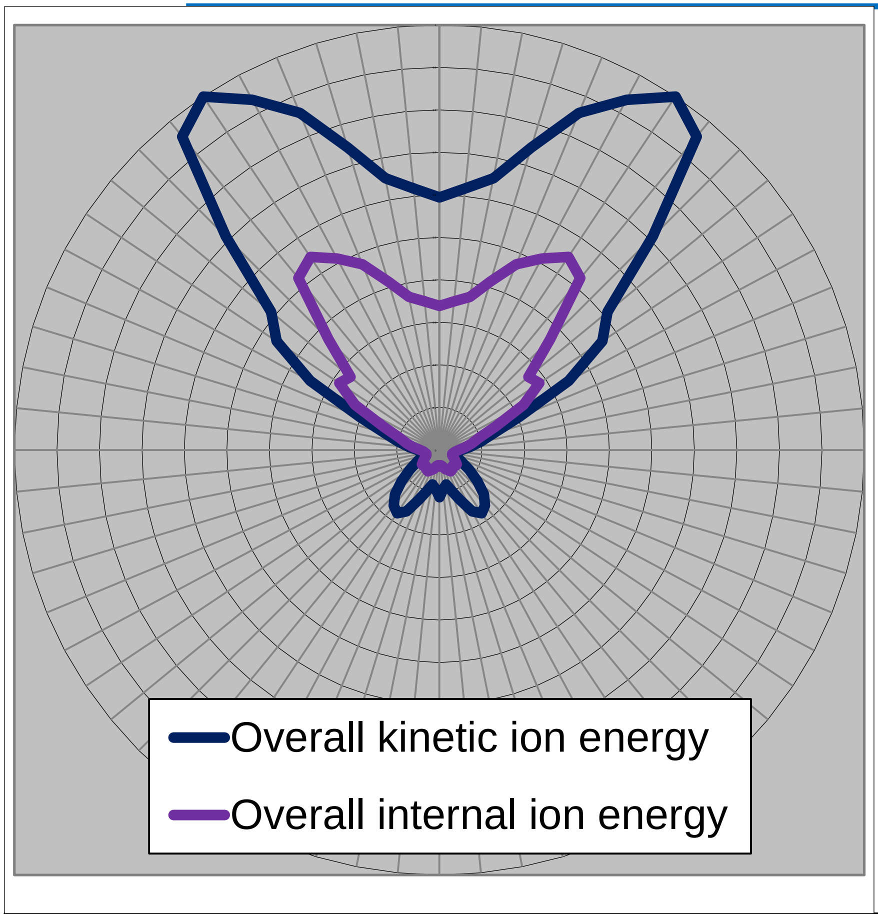
Polar angle dependencies for variant of slide 14

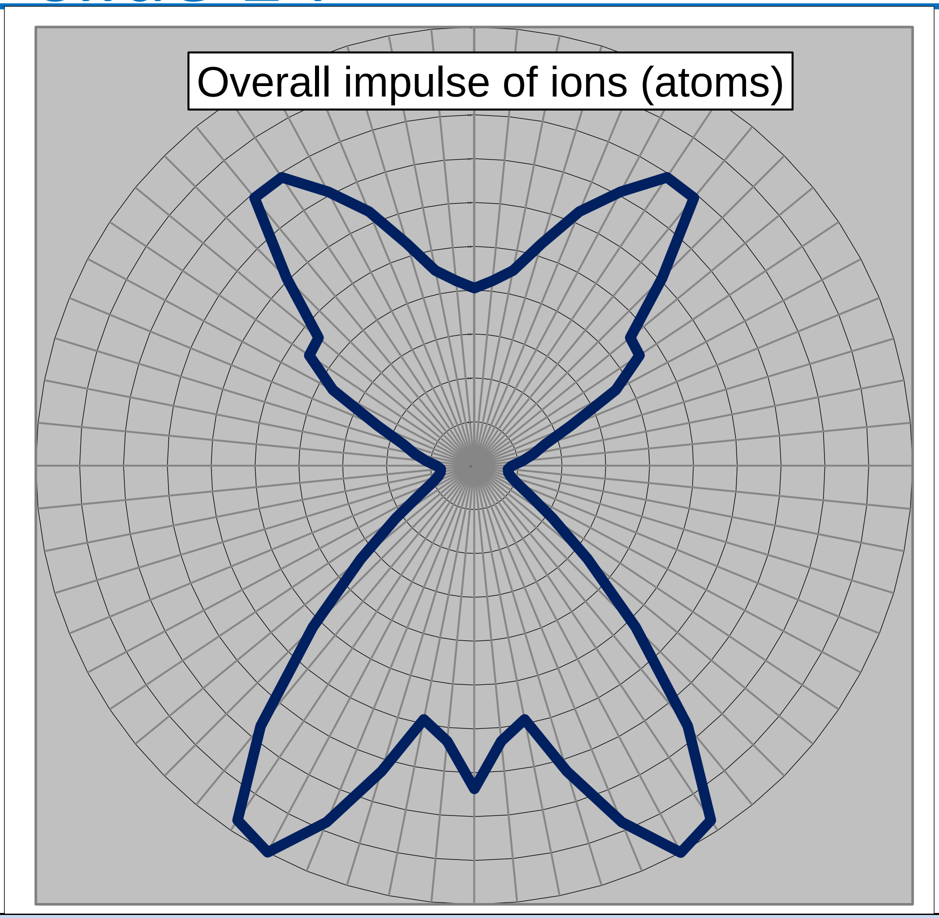




1. EUV in-band power is directed mainly in 2pi of collector direction (0.6 of full EUV emitted energy), ions energy reaching ~ 6 keV at $\theta = 0$
2. Mean ion charge polar distribution is looking mainly as EUV power reaching 15 at $\theta = 0$
3. Cold ions(atoms) are moving from the condenser mirror having up to ~45 grad to axis while number of fast ions in collector direction is an order of value smaller

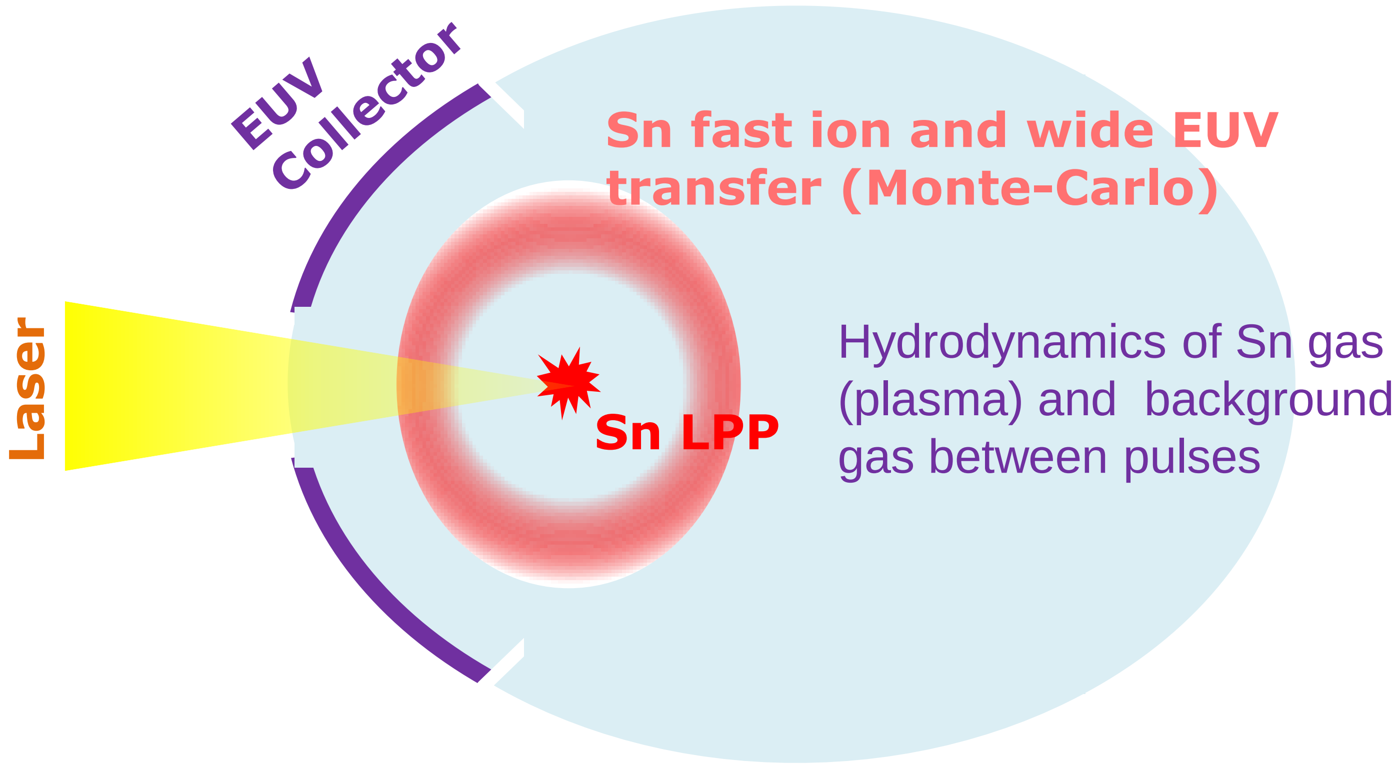
Polar angle dependencies for variant of slide 14



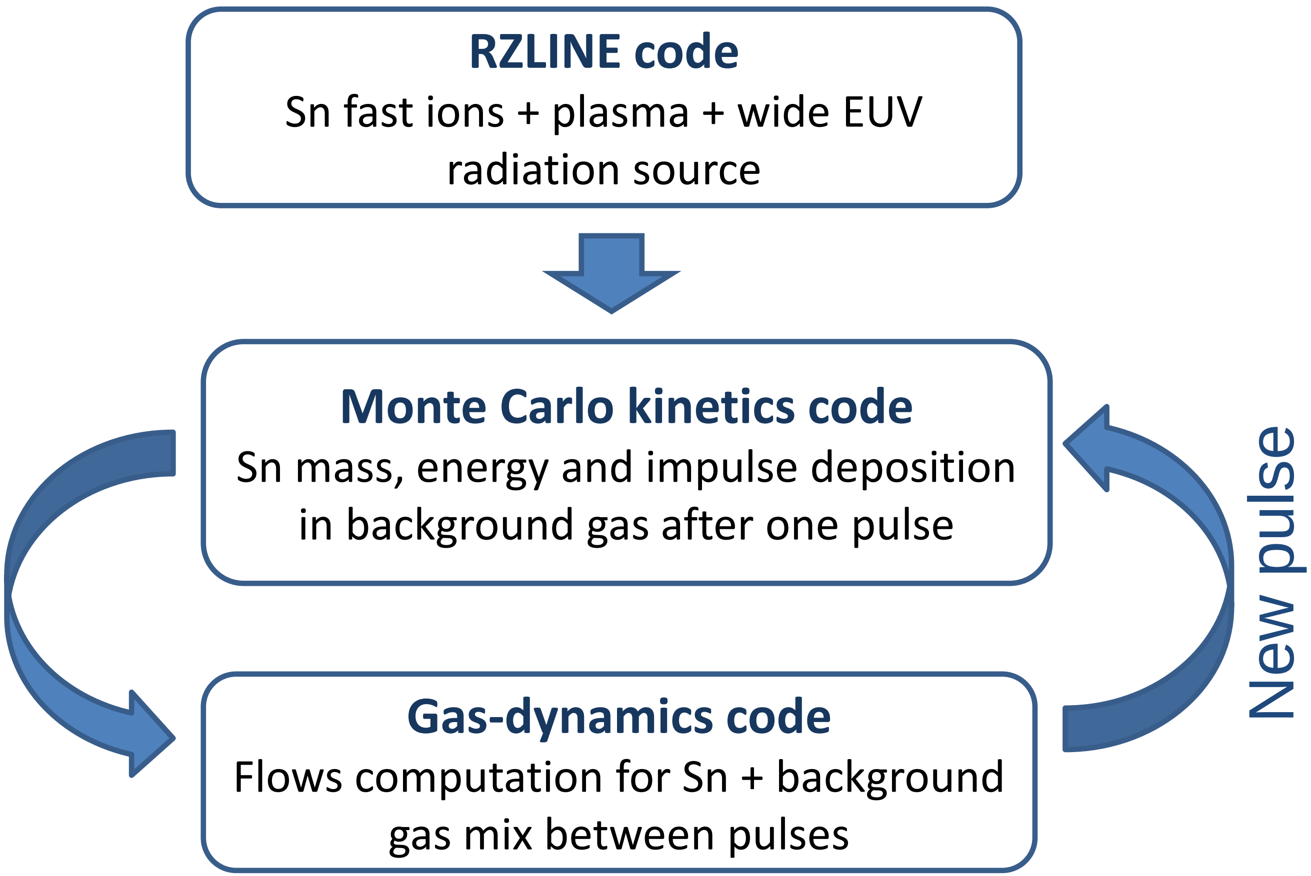


1. Ion energy is also directed to collector. Large part of internal energy (ionization, excitation…) can be transformed by recharging to radiation, while kinetic one is going entirely into buffer gas heating
2. Fast ions moving in direction to collector at ~ 45 grad to axis can travel large distance and transfer their impulse there. Sn flux to mirror can be possible.

Source chamber, multi-pulse modeling of processes there



2D Gas-dynamics modeling approach

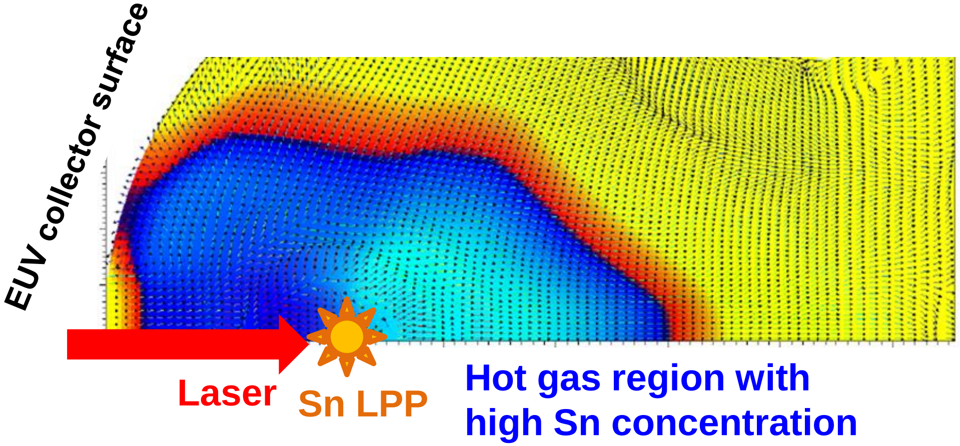


Main included processes

- Light spectra and its angular distributions
- Light absorption in gas mix
- Light reflection from mirror
- Momentum, energy and mass transfer from ions to gas mix
- Energy loss due to thermal radiation
- Plasma thermal conductivity
- Diffusion of tin in the background gas
- Tin accumulation on mirror
- Simplified source geometry
- Plasma chemistry at surfaces – under development

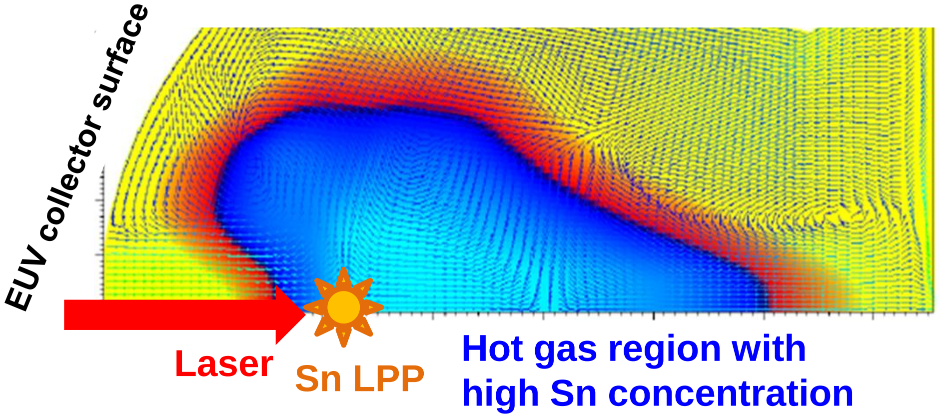
Model example, details are in appropriate poster s43

Example of model calculations for different source operation regimes



Background pressure $P_1 = P$

Sn ion flux reaches collector



Background pressure $P_2 = 2P$

Sn ion flux to collector suppressed

Model assists in determination of EUV source operation regime with low collector contamination rate

Conclusions

✓ The hybrid hydrodynamics model is developed for description of target geometry modification with laser pre-pulse

- Model indicates that spherical Sn droplet can be transformed into disk-type targets, matching typical CO_2 laser spot sizes (~ 300 um)

✓ RZLINE code modeling applied to disk-type Sn target for LPP indicates non-isotropic behavior of ions and EUV fluxes, which can enhance Sn atom flux on the mirror.

- Laser-pulse and target type engineering should be optimized simultaneously with collector defense system

✓ The hybrid Monte-Carlo and gas-dynamics model is developed for the description of Sn ions and radiation transport and plasma expansion in gaseous atmosphere

- model can be applied to study Sn debris fluxes in EUV source chamber
- model calculations indicate that operation regime with low collector contamination rates can be found

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